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SIMULATION OF A BIOFEEDBACK MICROCLIMATE COOLING SYSTEM USING A HUMAN THERMOREGULATION MODEL

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SIMULATION OF A BIOFEEDBACK MICROCLIMATE COOLING SYSTEM USING A HUMAN THERMOREGULATION MODEL

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14. ABSTRACT
Objectives of this project were to analyze heat transfer processes among skin, FCC and the environment, and develop algorithms for FCC characteristics and incorporate the algorithms into the existing Six Cylinder Thermoregulatory Model (SCTM). The FCC version of the SCTM was used to study the interaction between human thermoregulation and FCC and to determine FCC efficacy under wide ranges of metabolic rates and environmental conditions. The operational impact of the potential implementation of FCC is an extended system duration on a single battery charge compared with the same system operating in a constant cooling paradigm. Thus, the overall objective of this project is to define the conditions where operating duration is extended with FCC.

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EXECUTIVE SUMMARY

An autonomous, lightweight, efficient microclimate cooling system is needed to improve the operational capability and health state of Soldiers encapsulated in chemical protective clothing. Previous physiology studies demonstrated that feedback control cooling had the potential to improve cooling efficiency and extend operational duration (FCC uses skin temperature in a feedback loop to turn the cooling system on whenever the skin temperature reaches 35ºC or above, and turns the cooling system off whenever the skin temperature reaches 33ºC or below). However, these results were limited to the specific conditions studied. The primary purpose of this project was to determine the conditions under which FCC has efficacy (defined as increased human endurance and/or increased cooling system duration for a given battery capacity). Heat transfer processes among skin, FCC and environment were analyzed, and algorithms for FCC characteristics were developed and incorporated into the existing Six Cylinder Thermoregulatory Model (SCTM). The adapted SCTM was used to study the interaction between human thermoregulation and the FCC system and to determine FCC efficacy over a wide range of metabolic rates and environmental conditions. The simulation results (i.e., predicted endurance time, skin and core temperatures and system durations) reveal that FCC enhances the efficacy of the cooling system, reduces heat strain in comparison with no microclimate cooling conditions and extends the system duration by as much as 100% in comparison with the constant cooling conditions. However, magnitudes of the improvement in efficacy are dependent on the metabolic rates, environmental conditions, and ensembles worn. The simulation results defined the operating envelope where the FCC has efficacy and provided estimated FCC operational durations. The operating envelope where FCC is predicted to be effective encompasses 83% and 58% of the JSLIST/IOTV and Level A scenarios, respectively (see Tables 5 and 6 for details).

Based on the simulation results, it is recommended that FCC design should include three setting options: “On (Constant Cooling), “FCC (Feedback Control Cooling), and “Off” (No Cooling). This would provide users flexibility to choose the appropriate cooling to maximize operational duration.

INTRODUCTION

Soldiers operating in hot environments are vulnerable to heat illness and injuries; as a result, their health may be compromised and operational performance can become severely impaired, even at low activity levels. The need to wear protective clothing and equipment can further exacerbate a Soldier's heat stress, significantly diminishing his/her ability to reject metabolic heat to the ambient environment. As a result, body heat storage is increased, core temperature rises and physical and cognitive function can be significantly degraded. Depending on factors, such as environmental conditions, activity level, biophysical thermal characteristics of the protective clothing, and duration of exposure, personnel may experience symptoms ranging from physical discomfort to more severe, possibly life threatening, conditions (heat exhaustion or heat stroke).

Since 2010, technical developments in microclimate cooling technology have resulted in significant system weight and bulk reductions over legacy systems. However, their use has been limited to operators whose missions are relatively short and for whom power sources are readily available. An autonomous, lightweight, and energy efficient microclimate cooling system is needed to extend the operational capability and health state of users encapsulated in chemical/biological protective clothing.

Based upon work by Stephenson et al. (1), a personal cooling system using skin temperature feedback control reduced power consumption by 46% compared with one operating in a constant cooling paradigm, while reducing cardiovascular strain similarly. In this study, eight male volunteers exercised at a metabolic rate of approximately 425 W on a treadmill for 80 minutes (min) in a 30°C (11°C dew point) chamber. The skin temperature feedback control scheme maintained the volunteers' skin temperature between 33-35°C by turning the cooling system ON and OFF in response to real-time feedback. Below 33°C, vasoconstriction occurs, which effectively decreases heat transfer between the core and skin. Above 35°C, the temperature difference between the core and the skin is so diminished that minimal heat can be transferred to the skin. While this prior work quantified a significant improvement in system efficiency (i.e.,

reduced system power consumption), the feedback control cooling (FCC) was only studied in one condition (i.e., one environmental condition and one metabolic rate). Effectiveness of the FCC under other conditions is unclear. We postulate that the improvement in system efficiency by using FCC is dependent upon the specific conditions (i.e. environment, work rate, and protective ensemble) of use. It is necessary therefore, to determine the improvement in system efficiency under a wide range of conditions.

Objectives of this project were to analyze heat transfer processes among skin, FCC and the environment, and develop algorithms for FCC characteristics and incorporate the algorithms into the existing Six Cylinder Thermoregulatory Model (SCTM). The FCC version of the SCTM was used to study the interaction between human thermoregulation and FCC and to determine FCC efficacy under wide ranges of metabolic rates and environmental conditions. The operational impact of the potential implementation of FCC is an extended system duration on a single battery charge compared with the same system operating in a constant cooling paradigm. Thus, the overall objective of this project is to define the conditions where operating duration is extended with FCC.

METHODS

TERMINOLOGY

Constant Cooling (CC) – Cooling system is always in the “on” condition. Skin temperature feedback is not in use.

Cooling – Always refers to Feedback Control Cooling (FCC) unless otherwise stated.

Cooling System – A liquid circulating refrigeration system that circulates chilled fluid to a tube-lined Liquid Cooling Garment (LCG).

End Point – The time at which the simulation ended due to whichever occurs first: the predicted core temperature reaches 39ºC or after six hours pass.

Endurance Time – see Human endurance time.

Feedback Control Cooling (FCC) – Uses skin temperature in a feedback loop to turn the cooling system on whenever the skin temperature reaches 35ºC or above, and turns the cooling system off whenever the skin temperature reaches 33ºC or below. The cooling system starts in the ON condition, and then the skin temperature is measured and used to determine ON or OFF condition of the cooling system.

Human Endurance Time – Time the predicted core temperature reaches 39ºC or six hours pass, whichever occurs first.

Liquid Cooling Garment (LCG) – A tube-type personal cooling vest through which the Cooling System circulates a chilled fluid, removing metabolic heat.

Personal Thermal Management System (PTMS) – A vapor compression refrigeration system developed by RINI Technologies, Inc., that circulates a chilled fluid through a Liquid Cooling Garment.

System Duration – Time the cooling system is "viable"; that is, the total time until the battery energy of 240 watt-hours has been consumed (includes both the time the cooling system is ON and the time it is OFF, as long as the battery has not yet expired), or the End Point of the simulation, whichever occurred first.

SIMULATION OF THE COOLING SYSTEM

For the purposes of this exercise, the Cooling System consisted of the PTMS, Liquid Cooling Garment, and 240 watt-hour BB2590 battery. The PTMS was originally developed in accordance with a Government performance specification and qualified for use by military aircrew. The PTMS employs patented vapor compression cycle technology to chill coolant which is circulated through the network of tubing in the LCG to remove heat from the body. The simulations conducted here are based upon the heat extraction rate and power consumption characteristics of the PTMS and the energy capacity of the military's BB2590 battery. The LCG is in a vest configuration and consists of approximately 115 feet of small diameter tubing through which coolant is circulated.

Heat removal rate of a liquid cooling garment (LCG)

The rate of LCG heat removal from the human body depends on coolant inlet temperature (T_{in}), clothing insulation worn over the LCG, flow rate ($\dot{m}$), the LCG network tubing length, etc. The heat and mass exchange processes among the human body, LCG and environment are complex and include conduction, convection, evaporation, and condensation onto the tubing surface. After making the following assumptions: the temperature of skin covered by the LCG was constant and uniform, the heat transfer coefficient between coolant and skin was uniform and no heat exchange occurred between the LCG and external environment, an equation for estimating $\dot{Q}_{LCG}$ was derived from energy balance principles during the ON period (i.e. coolant circulation):

$$\dot{Q}_{LCG} = \dot{m}C_p \cdot (1 - e^{-\frac{hA}{\dot{m}C_p}}) \cdot (T_s - T_{in}) \qquad \text{(Eq. 1)}$$

where $\dot{Q}_{LCG}$ is in watts (W), $\dot{m}$ is the mass flow rate in kg/s, C_p is the specific heat of water 4200 J/kg °C, h is the heat transfer coefficient between coolant and skin in W/m^2°C, A is the tube surface area in m^2, T_s is mean skin temperature being cooled in °C, and T_{in} is coolant inlet temperature in °C.

Circulation stops during the OFF period, but the coolant continuously absorbs heat from the body and the coolant temperature increases until a new balance is reached. In addition to the assumptions made above to derive Eq. (1), it was further assumed that the coolant temperature was uniform with an initial value of T_{in} during the OFF period. Then, the heat absorbed by the coolant (Q_{LCG}) during this OFF period can be estimated by:

$$\dot{Q}_{LCG} = hA \cdot (T_s - T_{in}) \cdot e^{-\frac{hA}{wC_p}t} \qquad \text{(Eq. 2)}$$

where Q_{LCG} is heat absorbed by the coolant in joules, w is the mass of the coolant inside the LCG in kg, and t is duration of the OFF period in seconds.

Characteristics of the liquid cooling garment

Parameters of a LCG vest used in a previous study (2) were used for this analysis. The cooling vest design consisted of cotton fabric laminated around small tubing (2.5 mm, I.D.) divided into multiple parallel circuits. The tube lengths were 39 m, and contained approximately 0.19 kg of coolant inside the tubing. The flow rate was assumed to be 0.5 L/min. These parameters were used in the Eq. (1) and (2) to predict heat removal from the torso.

The LCG removes heat not only from the human body but also from the layered series of micro-environments within outer clothing when T_{in} is lower than the external air temperature (3). It is convenient to define a LCG/outer clothing efficiency (η) as the ratio of LCG heat removal rate ($\dot{Q}_{LCG}$) from the human body to the total heat removal rate of LCG ($\dot{Q}$), see Eq. 3 (3). The efficiency η is equal to one when the outer clothing has sufficient insulation and the heat exchange between LCG and the external environment is negligible. The LCG/outer clothing efficiency also varies with environmental conditions, insulation of the outer clothing, LCG configuration, etc. (3). Measurement of the cooling efficiency was beyond the scope of the project, thus an efficiency of 0.8 (3) was used in the simulation. Since the PTMS provides approximately 125 W (depending upon the environment), the heat removal rate from the body is 100 W.

$$\eta = \frac{\dot{Q}_{LCG}}{\dot{Q}} \qquad \text{(Eq. 3)}$$

Feedback control cooling (FCC)

For the purposes of this project, FCC consists of ON-OFF Cooling System control and aims to maintain the skin temperature between 33 – 35ºC. When the torso skin temperature is below 33ºC, the Cooling System is turned off and kept off until the torso skin temperature rises above 35ºC. When the torso skin temperature is above 35ºC, the Cooling System is turned on and kept on until the torso skin temperature fell below 33ºC.

The cooling capacity and power consumption of the PTMS varies with the ambient temperatures and can be described by:

$$CC = -2.8472 \cdot 10^{-4} \cdot {T_a}^3 + 7.949 \cdot 10^{-2} \cdot {T_a}^2 - 7.9847 \cdot T_a + 420.49 \quad \text{(Eq. 4)}$$

$$CP = 4.8163 \cdot 10^{-3} \cdot {T_a}^2 - 0.28957 \cdot T_a + 63.886 \quad \text{(Eq. 5)}$$

where CC is the cooling rate in W, T_a is the ambient temperature in ºF and CP is the power consumption in W. The coolant temperature difference entering and exiting the PTMS is described by:

$$\Delta T = \frac{CC}{\dot{m}C_p} \quad \text{(Eq. 6)}$$

where ΔT is the difference in coolant temperature entering and leaving the PTMS in ºC.

Cooling System duration on one B2590 battery charge when operated in Continuous Cooling mode is calculated as:

$$DL = \frac{240}{CP} \quad \text{(Eq. 7)}$$

where DL is the Cooling System duration in hours.

SIX CYLINDER THERMOREGULATION MODEL (SCTM)

A six cylinder thermoregulation model (4) was used for the modeling analysis. This model was adapted to simulate human thermoregulation for intermittent regional cooling (2) and used to optimize multi-loop cooling garment control system (5). In addition, this model has been validated for a wide range of applications, including both

heat and cold stress, various exercise loads, and various clothing ensembles (4;6). The SCTM represents the human body as six cylinders: the head, trunk, arms, legs, hands, feet (cylinders i=1…6) and a central blood pool. Each cylinder is further subdivided into four concentric layers representing the core, muscle, fat, and skin tissues (layers j=1…4). The model takes into account the radial dependency of the temperatures. A one-loop circulatory system is assumed, the central blood pool delivers the arterial blood to the tissues and the blood flows back to the pool through the veins. Temperature regulation is based on an integrated thermal signal which is composed of the weighted input from thermal receptors at various sites distributed throughout the body. The difference between this signal and its threshold is the afferent signal that activates the thermoregulatory mechanisms including sweat production, vasomotor function, and metabolic heat production. SCTM is briefly described below. For additional details, e.g., parameters and units, please refer to published papers which describe the SCTM (4;7).

The energy balance equation for each cylinder in one-dimensional cylindrical coordinates is:

$$\rho_i c_i \frac{\partial T_i}{\partial t} = \dot{M}_i - W_{ex,i} + \lambda_i \left\{ \frac{\partial^2 T_i}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T_i}{\partial r} \right\} + \beta_i Q_i \rho_b c_b (T_b - T_i) \quad \text{(Eq. 8)}$$

where $\rho_i c_i$ is the heat capacity of the tissue per volume, $T_i(r,t)$ is the temperature of the tissue, t is the time, λ is the thermal conductivity of the tissue, r is radius, β is the countercurrent factor by which the heat exchange between arterial blood and venous blood is approximated, $Q_i(r,t)$ is the blood flow rate per volumetric unit, $\rho_b c_b$ is the heat capacity of the blood flow, and $T_b(t)$ is the temperature of the blood pool.

The afferent signal for the thermoregulation system is calculated by the equation:

$$\mathrm{a(t)} = \sum_{i=1}^{6} \sum_{j=1}^{4} g_{ij} T_{ij}(r,t) - \mathrm{a}_0 \quad \text{(Eq. 9)}$$

where a(t) is the afferent signal for the thermoregulation system, g_{ij} is the weighting factor, and a_0 is the threshold. The integrated afferent signal is then transformed into efferent signals using distribution factors which have different values for sweat production and for blood flow. The sweat production, for example, is calculated as:

$$E_i = E_{i0} + \varepsilon_{Ei} a \qquad \text{(Eq. 10)}$$

where ε_{Ei} is the distribution factor for evaporation, and E_{i0} is the basal evaporation value.

The two heat removal equations rates were incorporated into the boundary equations of the model to adjust for LCG effects. The modified boundary equation is:

$$-\lambda \frac{\partial T}{\partial r} = R + C + E + \frac{\dot{Q}}{S} \qquad \text{(Eq. 11)}$$

where λ is the thermal conductivity of tissues in W/m·°C, T is the tissue temperature in °C, r is the radius in meters, R is the irradiative heat exchange in W/m^2, C is the convective heat exchange in W/m^2, E is the evaporative heat exchange in W/m^2, $\dot{Q}$ is the LCG heat removal rate in W, S is the surface area in m^2. This revised boundary equation considers not only the heat exchange between the body, skin and environment but also the heat exchange between the body, skin and LCG.

ENDURANCE TIME AS A THERMAL PERFORMANCE CRITERIA

Endurance time, i.e., the time for the core temperature to reach a defined threshold value, is often used as a measure of PPE thermal performance. Endurance time is an approximation of the time that a wearer can work in a warm or hot environment without becoming a heat casualty, and may be expressed, for example, in terms of maximum allowable exposure time (8), tolerance time (9), or safe exposure time. It is particularly useful in planning shift changes or rotation for teams working under extreme conditions such as hazardous waste clean-up operations. The purpose of a cooling system is to extend the endurance time and allow wearers to work safely for a longer period relative to no cooling conditions.

Heat exhaustion may occur at a low core temperature of about 38.3°C, depending on factors, such as hydration and heat acclimation (10). Therefore, selection of the threshold value for the core temperature should take into account mission needs, protection requirements, acceptable risk levels, etc. Previous studies have used a threshold core temperature of 39°C (10-14). Thus, in this paper, 39°C is used in the modeling analysis where endurance time is defined as the length of time until the core temperature increases to 39°C.

SIMULATION CONDITIONS

Ensembles outside the LCG:

Two protective ensembles to be modeled were selected. These ensembles were chosen based on several criteria. These criteria include that the ensembles are in use by U.S. military personnel, thermal and evaporative resistance properties are known (i.e. measured on a Thermal Manikin), and the garments represent two thermal extremes, that is, high thermal resistance with low evaporative resistance, and low thermal resistance with high evaporative resistance.

The two ensembles are:

1) Joint Service Light Integrated Suit Technology (JSLIST) worn over the Flame Resistant Army Combat Uniform (FR ACU) in Mission Oriented Protective Posture 4 (MOPP 4) + Improved Outer Tactical Vest and Army Combat Helmet (JSLIST/IOTV), thermal and evaporative resistances: 0.39 $m^2 \cdot {}^oC \cdot W^{-1}$, 66.9 $m^2 \cdot P_a \cdot W^{-1}$ (2.49 clo, i_m 0.35)
2) Level A ensemble (Kappler® Zytron® 500 SBRN Protective Ensemble) worn by Army National Guard 1st Civil Support Team for Weapons of Mass Destruction (Level A), thermal and evaporative resistances: 0.27 $m^2 \cdot {}^oC \cdot W^{-1}$, 270.9 $m^2 \cdot P_a \cdot W^{-1}$ (1.73 clo, i_m 0.06)

Environmental conditions:

Since the goal of the current effort is to define the envelope in which FCC will enhance the efficiency of a personal cooling system, it is necessary to conduct the

simulations over a wide range of temperature and humidity conditions. Furthermore, Army Regulation 70-38, “Research, Development, Test and Evaluation of Materiel for Extreme Climatic Conditions” provides guidance for the selection of environmental conditions. Therefore a matrix of temperature and humidity conditions was constructed which covers most of the environmental “space” included in the Army Regulation (AR), while avoiding conditions outside those specified in the AR. The matrix is as follows:

1) 24ºC, Relative Humidity (RH) = 3%, 25%, 50%, 75% and 100%
2) 30ºC, RH = 3%, 25%, 50% and 75%
3) 36ºC, RH = 3%, 25%, and 50%
4) 42ºC, RH = 3%

A wind speed of 1 m/s was used for all simulations.

Metabolic rates:

As with environmental conditions, it is necessary to conduct simulations over a range of metabolic rates in order to define the envelope in which FCC will enhance the efficiency of a cooling system. For the purposes of this study, simulations were run at a resting metabolic rate, and over a range of metabolic rates from 200 to 500 W, at 50 W intervals. This range covers most of the metabolic rates of Soldiers engaged in chemical biological defense training (15) or light and moderate military tasks in MOPP 0 and MOPP 4 (16).

1) Resting
2) 200 W to 500 W, every 50 W

Simulation terminates when either of following criteria is met:

1) Predicted core temperature reaches 39ºC
2) Six hours pass

RESULTS

Figures 1, 2 and 3 are sample predicted results of the core temperature, torso skin temperature and heat removal rate with JSLIST/IOTV at an environment of 30ºC, 75% RH and 1m/s wind speed. Figure 1 is a typical core temperature response to FCC as a function of time at eight metabolic rates. At the metabolic rate of 250 W, the cooling system is able to maintain the core temperature at about 37.1ºC for approximately 310 min. After that, the battery is consumed, the cooling system stops and the core temperature starts to rise. At a metabolic rate of 350 W, the cooling system is unable to maintain a constant core temperature, core temperature rises continuously, and the battery is consumed after approximately 220 min. At a metabolic rate of 400 W, the core temperature rises continuously and reaches the 39 ºC threshold before the battery is consumed, after approximately 170 min.

Figure 2 shows predicted torso skin temperature response to FCC as a function of time for 30ºC, 75% RH, and 1 m/s wind speed, wearing JSLIST/IOTV. At a metabolic rate of 250 W, the cooling system is ON or OFF as controlled by the FCC. The cooling system is able to maintain the torso skin temperature between 33°C - 35 ºC until the battery is consumed at 310 min. In this case, FCC extends the system duration from 193 min (operating in a constant cooling mode) to 310 min. However, at metabolic rates of 300 W or higher, the cooling system is in the ON or OFF condition during approximately the first 50 minutes and then operates continuously since the skin temperature remains above 33 ºC.

Figure 3 shows typical predicted heat removal rates from the torso for FCC at 30 ºC, 75% RH, and 1 m/s wind speed with JSLIST/IOTV. The heat removal rates are

about 110 W when the cooling system is ON and drops quickly when the cooling system is OFF.

Figure 4 shows human endurance times with and without FCC while wearing JSLIST/IOTV at 30ºC, 50% RH, and 1m/s wind speed. The endurance times are the times when predicted core temperature reaches 39ºC. The results clearly show that the cooling system increases human endurance time in comparison with no cooling conditions.

Figure 5 shows human endurance times with and without FCC while wearing Level A at 30ºC, 75% RH and 1m/s wind speed. The results clearly show that the cooling system increases the endurance times in comparison with no cooling conditions. The differences between Figures 4 and 5 show that the efficacy of the cooling system is influenced by the ensemble worn outside the LCG.

Table 1 summarizes endurance times for JSLIST/IOTV with and without FCC under all 104 simulated conditions. The gray areas indicate that the ON-OFF pattern continues during all the periods before the battery is consumed (e.g., 250 W in Figure 2) while the white areas show that the ON-OFF pattern was only maintained during the first 50 min or so and then becomes constant (e.g., 300 W in Figure 2).

Table 2 summarizes endurance times for Level A with and without FCC for 104 simulations. The differences between Table 1 and Table 2 further demonstrate that FCC efficacy is influenced by the ensemble worn outside LCG. In addition, Tables 1 and 2 demonstrate that FCC extends the endurance times, but the increase is conditional on metabolic rate, environmental condition and ensemble worn.

Table 3 shows the predicted core temperature with and without FCC at the time of the no cooling (NC) end point for JSLIST/IOTV. This table shows the extent to which the use of FCC reduces a Soldier's core temperature, thus reducing heat strain, compared to not having any cooling. The core temperatures with FCC are always less than or equal to the correspondent core temperatures without FCC.

Table 4 is the predicted core temperature with and without FCC at the time of the NC end point for Level A. This table shows the extent to which the use of FCC reduces a Soldier's core temperature, thus reducing heat strain, compared to not having any cooling. The core temperatures with FCC are always less than or equal to the correspondent core temperatures without FCC.

Table 5 shows predicted system durations when the Cooling System is operated in FCC mode ("System Duration FCC") for JSLIST/IOTV compared to system durations if used in a constant cooling (CC) mode ("System Duration CC").

System Duration CC was calculated from Eq. 4. The System Duration FCC is the sum of the time the system was ON, plus the time the system was OFF, until the simulation ended or the battery expired, whichever occurred first. The first comparison between FCC and CC in Table 5 is the "System Duration Extension," which is calculated as the System Duration FCC minus the System Duration CC. This value shows the extent to which the use of FCC extends the viability of the Cooling System compared to CC. Table 5 shows that the use of FCC can extend the system duration by more than 3 hours (in excess of 100%) compared to CC in some scenarios.

An "n/a" in the System Duration Extension column indicates that the use of FCC does not show any improvement over CC in that scenario. These results appear in

yellow in Tables 5 and 6, and occur in the more extreme scenarios (more extreme environmental conditions and higher metabolic rates). The simulations indicate that the human would reach their endurance limit before the battery energy was fully consumed. This is true whether the Cooling System was operating in FCC or CC mode.

Table 5 also indicates whether there was any energy remaining in the battery at the end of the simulation (shown as “Battery Time Remaining”), which represents the time the Cooling System would have continued to run (system ON continuously) if needed.

Table 6 shows the predicted FCC durations, CC durations, and comparisons between the two for CST Level A, in a similar fashion as Table 5 for JSLIST/IOTV.

DISCUSSION

The USARIEM SCTM was adapted to the simulation of thermal interaction between the human, FCC and the environment to determine FCC efficacy under a wide range of metabolic rates and environmental conditions. The simulation results (i.e., predicted endurance time, core temperatures and system durations) reveal that FCC enhances the efficacy of the cooling system, reduces heat strain in comparison with no FCC conditions and extends the system duration by as much as 100% in comparison with the constant cooling conditions. However, magnitudes of the improvement and extension are dependent on the metabolic rates, environmental conditions, and ensembles worn. These simulation results defined the operating envelope where the FCC has efficacy.

The operating envelope where FCC has efficacy includes 83% and 58% of the JSLIST/IOTV and Level A scenarios, respectively (see Tables 5 and 6 for details).

However, the effect is more pronounced at moderate metabolic rates and less extreme environmental conditions. The heat balance equation of body tissues, i.e., Eq. 8, shows that metabolic heat production is one of the key factors increasing body temperature. To maintain body temperature, the cooling system is used to remove excess heat from the body, as described by heat balance equation at the skin surface, Eq. 11. As shown in Figure 3, the heat removal rate of the cooling system is approximately 115 W. Thus, the cooling system is only able to maintain body heat balance or keep the core temperature below 39ºC under certain conditions, i.e., combinations of metabolic rate and environmental conditions.

The efficacy of FCC decreases as environmental temperature or humidity increases. In addition to the LCG heat removal, the body heat loss at the skin surface is related to the environmental conditions and clothing worn. When body heat loss decreases due to environmental conditions, the amount of heat required to be removed by the cooling system increases and FCC ON time increases, thus the efficacy is reduced. For example, at the metabolic rate of 300 W with JSLIST/IOTV, the predicted system duration shown in Table 5 was 321 min at 30ºC/RH25% and 206 min at 36ºC/RH25%.

The influence of the ensemble worn over the LCG on FCC efficacy are clearly shown in the simulation results in Tables 1, 3, and 5 for JSLIST/IOTV and Tables 2, 4, and 6 for Level A. For example, at 30ºC/RH50% and metabolic rate of 400 W, the predicted endurance times were 239 min with JSLIST/IOTV shown in Table 1 and 135 min for Level A shown in Table 2, respectively. When environmental temperatures increase, evaporative heat loss becomes a major heat loss avenue. The evaporative

heat loss is inversely related to ensemble vapor resistance. The Level A ensemble is impermeable and has high vapor resistance of 270.9 $m^2 \cdot P_a \cdot W^{-1}$ (i_m = 0.06) which is significantly higher than the vapor resistance of JSLIST/IOTV 66.9 $m^2 \cdot P_a \cdot W^{-1}$ (i_m = 0.35). Therefore, evaporative heat loss is lower when wearing Level A, the amount of excessive heat required to be removed by the cooling system is higher and FCC efficacy is lower. The thermal insulation of JSLIST/IOTV is 0.39 $m^2 \cdot {}^oC \cdot W^{-1}$ (2.49 clo) and the insulation of Level A is 0.27 $m^2 \cdot {}^oC \cdot W^{-1}$ (1.73 clo). Insulation of protective ensembles prevent the LCG from absorbing heat from the environment (circulating liquid temperature is about 20ºC) and increase LCG efficiency (3). Therefore, from the perspective of FCC efficacy, JSLIST/IOTV seems to represent a better case (high insulation and low vapor resistance) than Level A (low insulation and high vapor resistance).

The FCC approach seeks to optimize energy savings, extension of operational duration and the management of human thermal status. Thus, FCC is designed to keep the torso skin temperature between 33ºC and 35ºC, turning OFF the cooling system when the torso skin is below 33ºC and turning ON the cooling system when the torso skin is above 35ºC. Thus, even when fully optimized, the thermal physiology status could only be maintained at equilibrium under some conditions. At more extreme conditions, the core temperature continued to rise. However, in practice, exercise intensity varies during different operational phases and the cooling required changes. FCC would only be ON when cooling is required, thus saving energy and extending system duration.

Physiological feedback automatic control of a LCG system has been extensively studied (5;17-22) since NASA attempted to develop automatic control for a LCG in a space suit in the 1970s (18). An automatic controller for mean skin temperature with set-point adjustment according to the metabolic heat production was able to maintain core body temperature in heat balance status (5;19). Another controller used the mean body temperature as feedback to account for the thermal state of subjects as they were being cooled by the LCG (22). Measurement of CO_2 production as an indication of metabolic rate was used as a signal to initiate the control response. The controller was able to maintain thermal neutrality for the subject over a wide range of environmental and transient metabolic states. The purposes of these two controllers are to maintain heat balance or thermal neutrality. Thus, both controllers require cooling units that provide adequate amount of cooling. In comparison with these complicated cooling control approaches, FCC is simple and easy to implement.

In Tables 5 and 6, the green and blue regions show where FCC has efficacy; that is, the system duration in FCC mode is greater than system duration in CC mode, while also extending human endurance time.

As shown in Tables 5 and 6, the System Duration Extensions for FCC over CC are generally greater at lower metabolic rates and less extreme environmental conditions. The greatest System Duration Extension occurred at rest, at 36°C, RH3%, and is more than 3 hours (182 minutes) which represents a 102% increase compared to CC, and there is still 59 minutes of battery life remaining (JSLIST/IOTV). At more extreme environmental conditions, and greater metabolic work rates, System Duration Extension is less dramatic, but still significant. For example, at a 500 W metabolic rate,

at 30°C, RH3%, System Duration FCC is about 10% greater than System Duration CC, which may be significant for some users. This indicates that FCC is performing as designed, delivering cooling only when cooling is required, and makes full use of the energy stored in the battery.

At very extreme environments coupled with high metabolic work rates, FCC does not show improvement over CC largely because the Human Endurance Time is short. In these scenarios, highlighted in yellow in Tables 5 and 6, the cooling need exceeds the capability of the Cooling System, and even CC is not enough to keep the user from excessive heat strain. In these situations, it is intended that FCC should function as a CC device to maximize cooling benefit to the user. There is no reason to save battery energy and extend system duration if the human endurance time is shorter than the battery life.

However, Tables 5 and 6 show that in many of these most extreme scenarios, the System pulsed at least once at the beginning of the simulation before becoming continuous, indicating that the Cooling System did not function as a CC device, as intended. That is, the Cooling System turned off in response to skin temperature data at the beginning of the mission, but the additional metabolic heat storage caused the user to reach the core temperature limit in a shorter time period than in the same CC scenario. Since the Cooling System did not fully function as a CC device under these extreme conditions, but rather, turned OFF and ON one or more times at the start of these simulations, it is necessary to improve the FCC control scheme. Further work to develop an improved FCC control scheme to ensure that the cooling system will operate as a CC device under these extreme scenarios is recommended.

In the yellow region of Tables 5 and 6, the Battery Life Remaining generally increased with increasingly severe environmental conditions. This is due to the shorter Human Endurance Times in these scenarios.

It is important to note that these simulation results (e.g. Human Endurance, ON – OFF cycles, System Duration, Battery Time Remaining, etc.) are based on the general performance characteristics of the current Cooling System. A cooling system with a different cooling capacity will yield different specific results. However, the general trends should be applicable to many cooling systems.

The simulation is a theoretical analysis and human studies are required to validate the simulations.

CONCLUSIONS

Algorithms for FCC thermal characteristics were developed and incorporated into the existing SCTM. The SCTM adapted to FCC was used to simulate interaction between FCC and human thermoregulation. The simulation results (i.e., predicted endurance time, core temperature and system duration) reveal that FCC enhances the efficacy of the cooling system, reduces heat strain in comparison with no FCC conditions and extends the system duration by as much as 100% in comparison with the constant cooling conditions. However, magnitudes of the improvement and extension are dependent on metabolic rate, environmental conditions, and ensembles worn. These simulations defined the operating envelope where FCC has efficacy and provided estimated FCC operational duration, as indicated by the green and blue regions of Tables 5 and 6. The green regions represent the scenarios where system duration in FCC mode exceeds system duration in CC mode, battery life remains, and

core temperature does not reach 39°C in six hours. The blue regions represent the scenarios where system duration in FCC mode exceeds system duration in CC mode, the battery was fully consumed, and core temperature reaches 39°C within six hours. The yellow regions represent scenarios where FCC shows no advantage over CC and the Cooling System should operate in continuous mode.

Based on the simulation results, it is recommended that FCC design should include three switch options: “On” (Constant Cooling), “FCC” (Feedback Control Cooling), and “Off” (No Cooling). This would provide users flexibility to choose the appropriate cooling to maximize operational duration.

Figure 1. Predicted core temperatures versus time for FCC with JSLIST/IOTV at 30ºC, 75% RH, 1m/s wind speed, using one 240 watt-hour battery

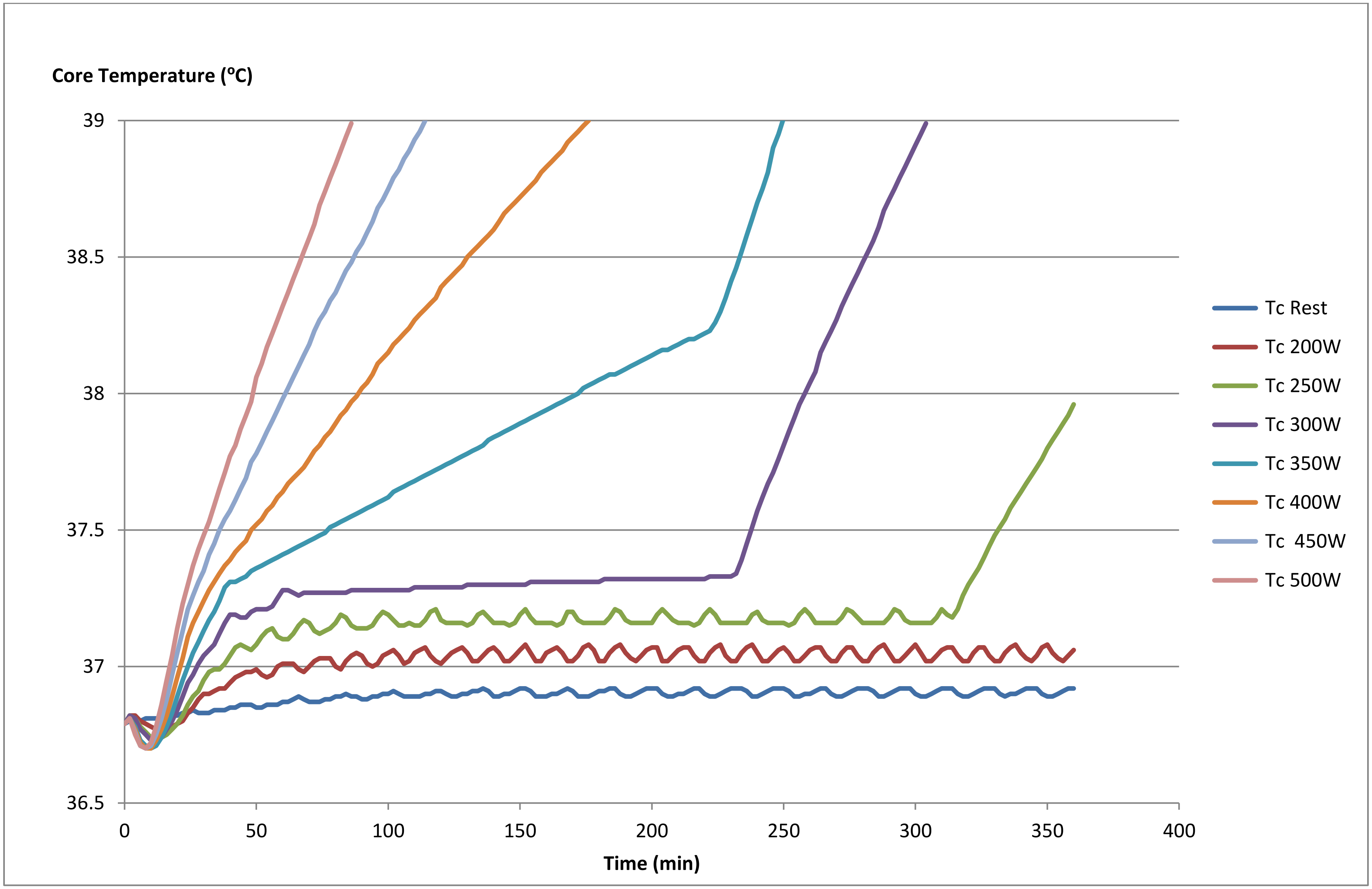

Figure 2. Predicted torso skin temperatures versus time with FCC for JSLIST/IOTV at 30ºC, 75% RH, 1m/s wind speed, using one 240 watt-hour battery

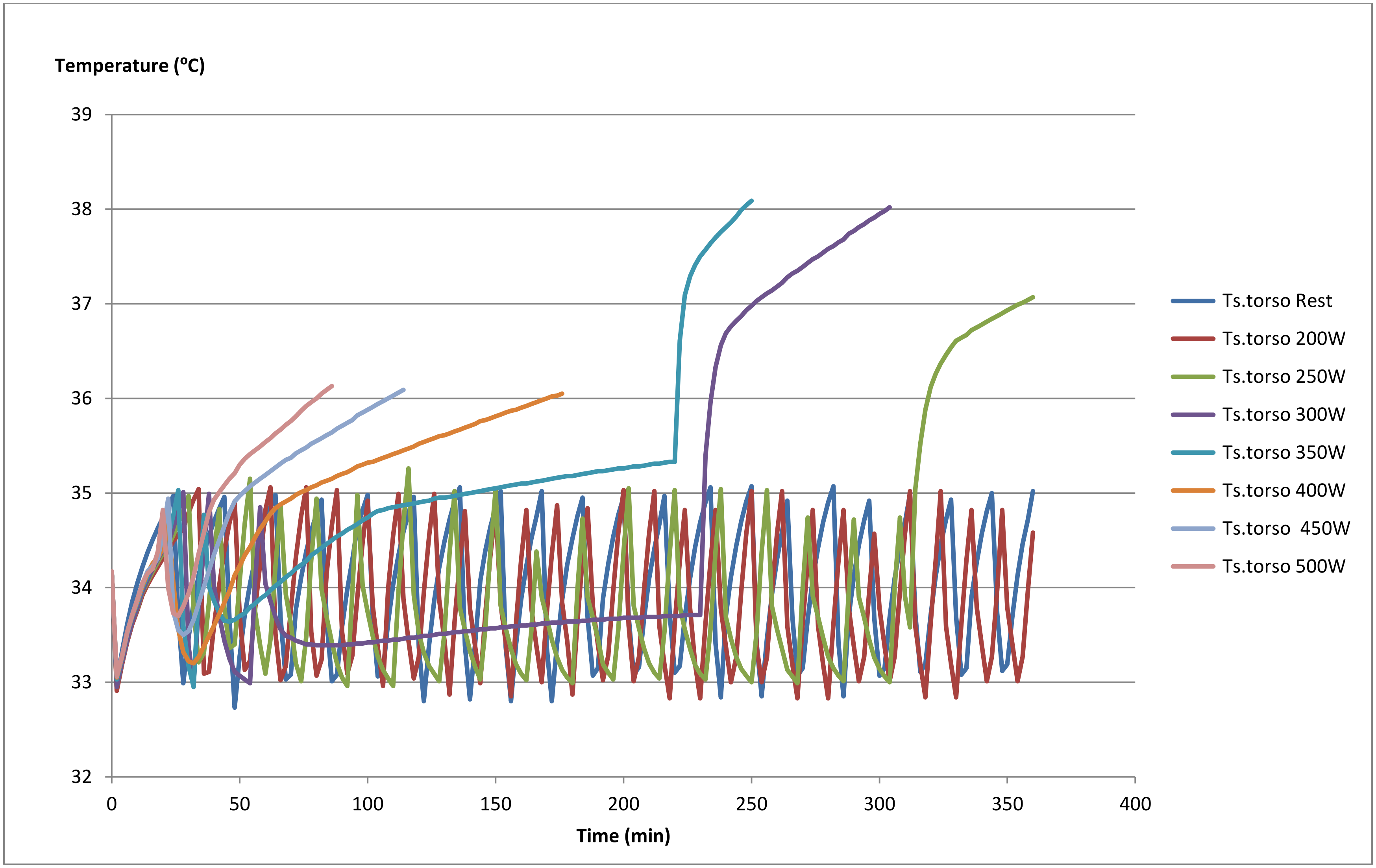

Figure 3. Predicted heat removal rates of the liquid cooling garment versus time with FCC for JSLIST/IOTV at 30ºC, 75% RH, 1m/s wind speed, using one 240 watt-hour battery

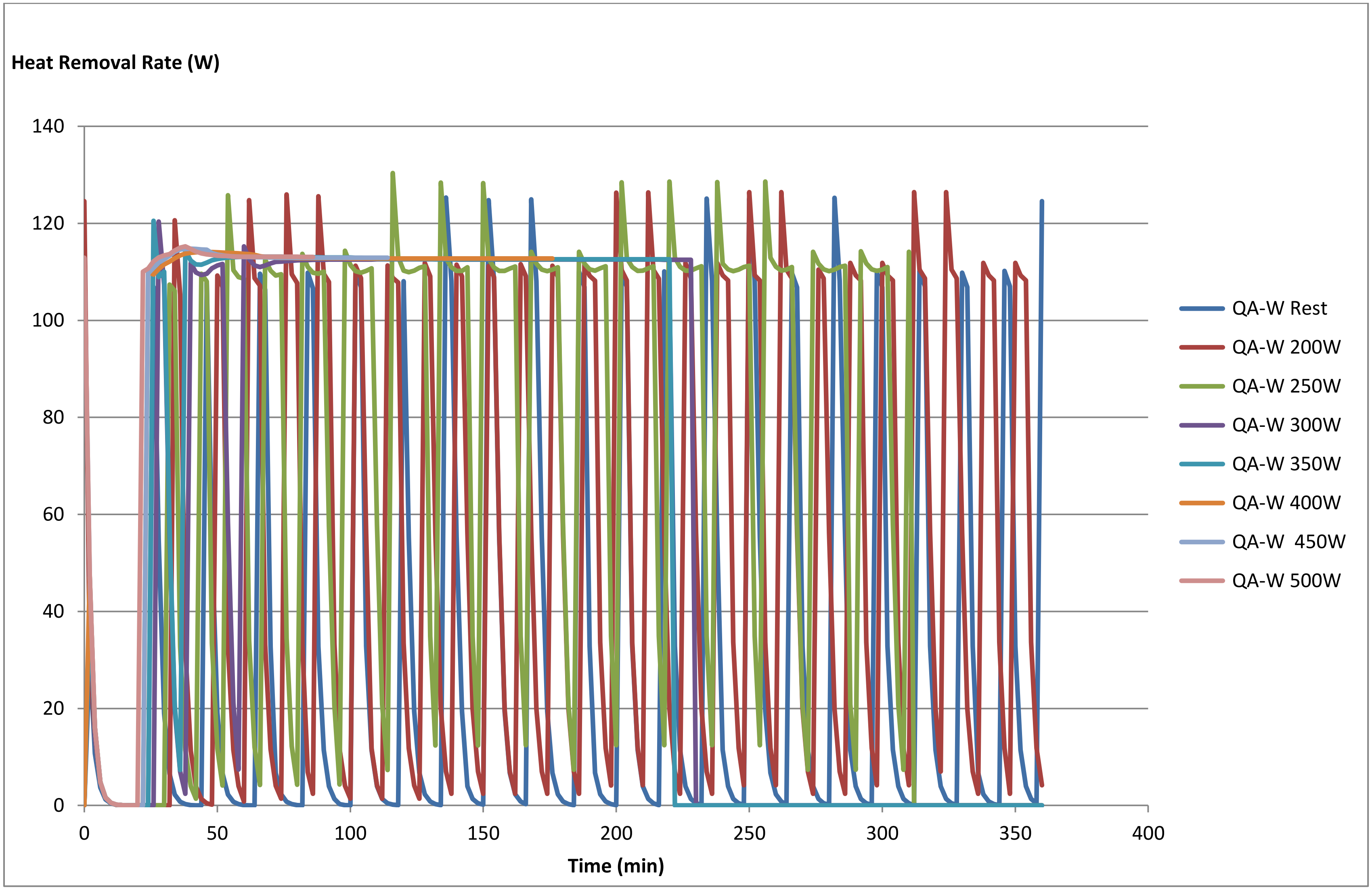

Figure 4. Predicted human endurance times with and without FCC for JSLIST/IOTV at 30ºC, 75% RH, 1m/s wind speed, using one 240 watt-hour battery

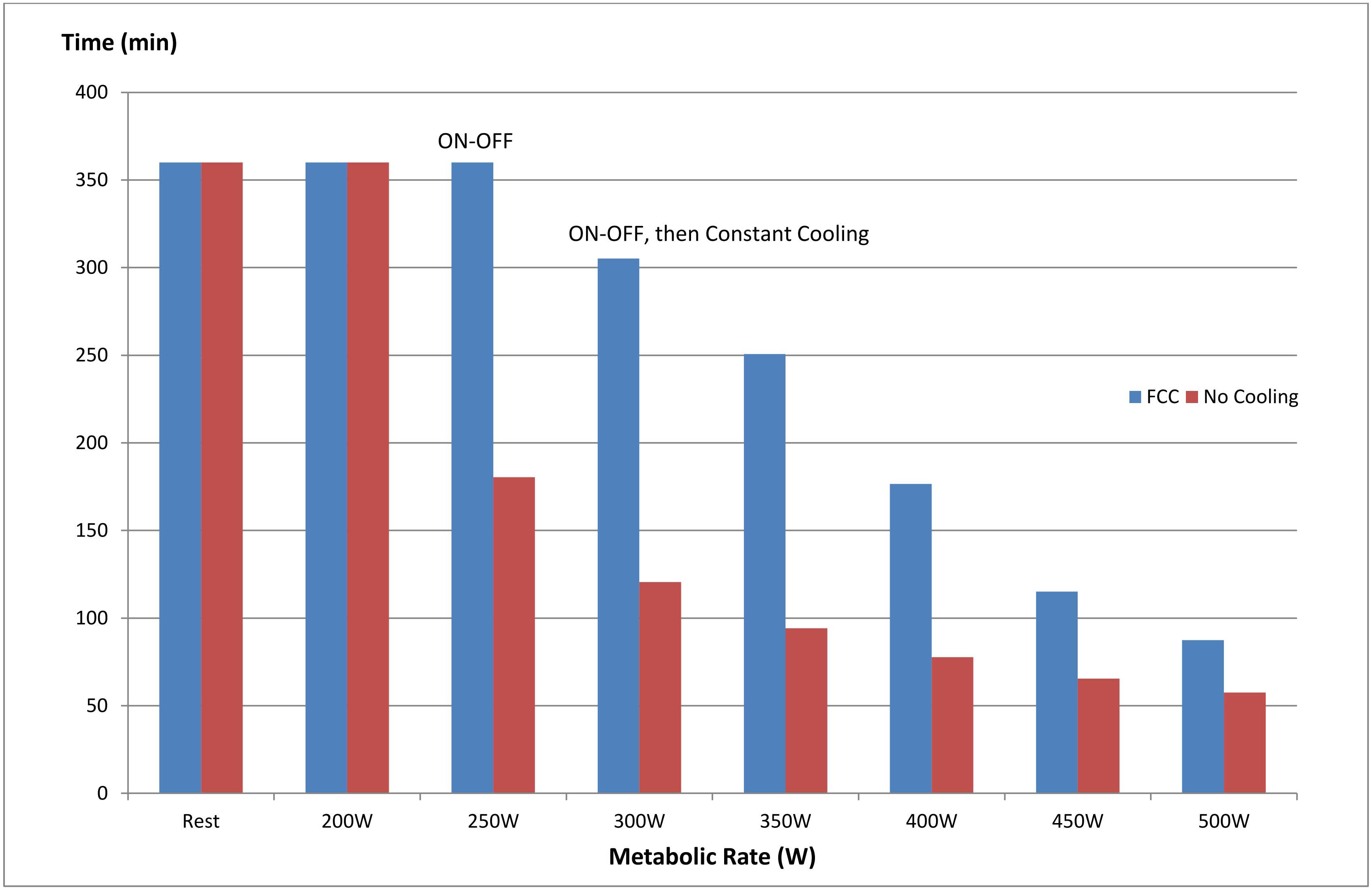

Figure 5. Predicted human endurance times with and without FCC for Level A at 30ºC, 75% RH, 1m/s wind speed, using one 240 watt-hour battery

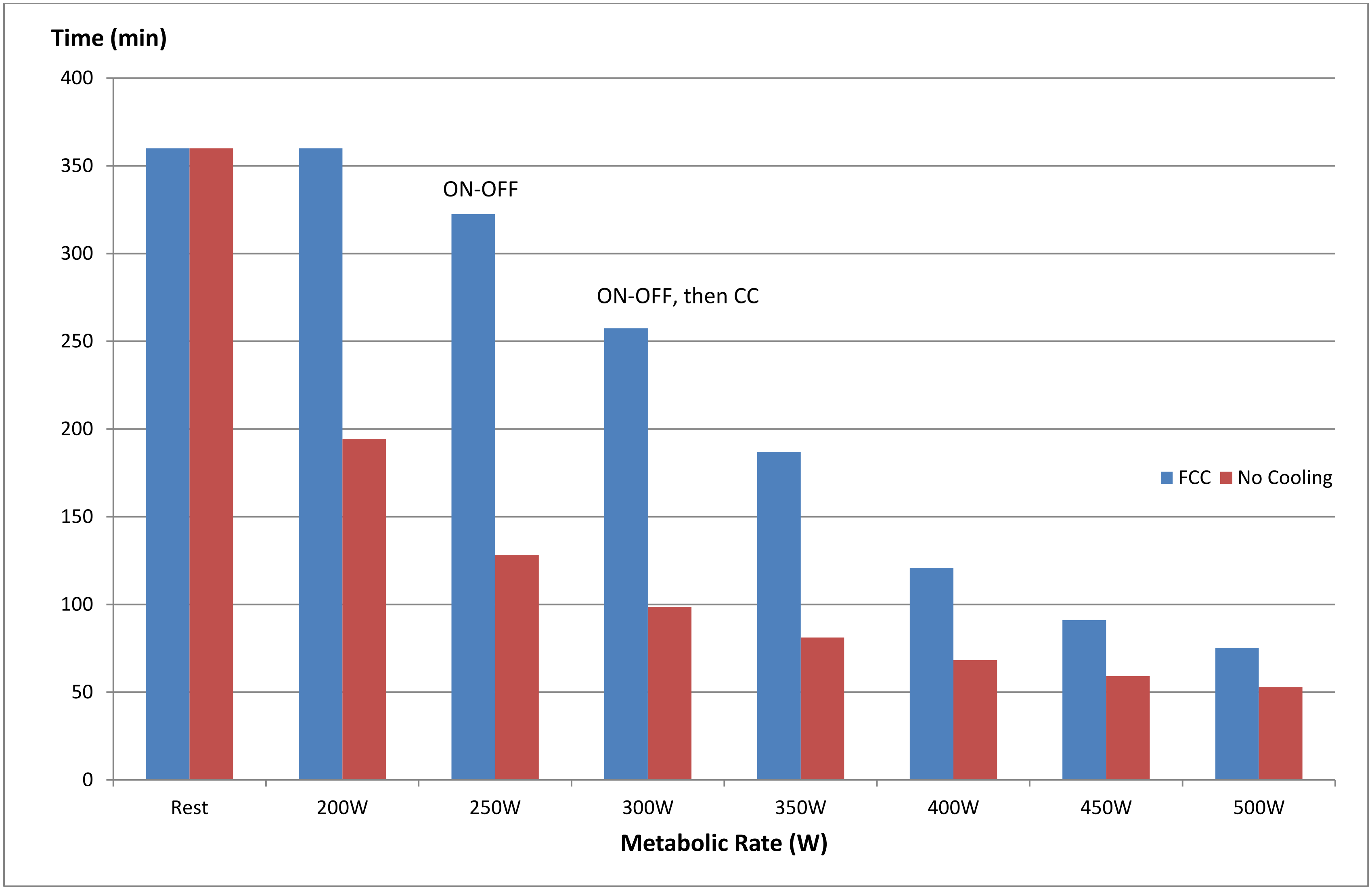

Table 1. Predicted human endurance time (min) with and without FCC for JSLIST/IOTV

	Rest		200W		250W		300W		350W		400W		450W		500W	
	FCC	NC	FCC	NC	FCC	NC	FCC	NC	FCC	NC	FCC	NC	FCC	NC	FCC	NC
24ºC/RH3%	360	360	360	360	360	360	360	360	360	360	360	179	311	116	270	89
24ºC/RH25%	360	360	360	360	360	360	360	360	360	263	360	144	294	102	252	83
24ºC/RH50%	360	360	360	360	360	360	360	360	360	179	316	119	274	92	202	76
24ºC/RH75%	360	360	360	360	360	360	360	239	360	140	294	103	245	83	145	69
24ºC/RH100%	360	360	360	360	360	360	360	172	320	117	267	91	183	76	156	65
30ºC/RH3%	360	360	360	360	360	360	360	360	360	200	300	125	256	94	215	77
30ºC/RH25%	360	360	360	360	360	360	360	257	329	144	275	103	231	83	142	70
30ºC/RH50%	360	360	360	360	360	315	360	160	288	112	239	89	158	74	106	64
30ºC/RH75%	360	360	360	360	360	180	305	121	251	94	177	78	115	65	87	58
36ºC/RH3%	360	360	360	360	360	360	360	226	289	134	246	98	206	80	125	68
36ºC/RH25%	360	360	360	360	360	238	299	139	253	102	208	83	130	70	95	60
36ºC/RH50%	360	360	360	227	306	138	250	102	203	83	128	70	94	60	77	53
42ºC/RH3%	360	360	360	360	360	290	287	151	236	106	198	86	136	71	97	62

Gray: ON-OFF during all the periods until the battery is consumed; NC: no cooling (without FCC)

Table 2. Predicted human endurance time (min) with and without FCC for Level A

	Rest		200W		250W		300W		350W		400W		450W		500W	
	FCC	NC	FCC	NC	FCC	NC	FCC	NC	FCC	NC	FCC	NC	FCC	NC	FCC	NC
24ºC/RH3%	360	360	360	360	360	360	360	214	360	135	291	101	239	82	134	70
24ºC/RH25%	360	360	360	360	360	360	360	192	358	127	280	97	206	80	125	68
24ºC/RH50%	360	360	360	360	360	341	360	173	330	118	268	93	178	77	115	65
24ºC/RH75%	360	360	360	360	360	280	360	157	312	111	257	89	158	74	107	64
24ºC/RH100%	360	360	360	360	360	238	360	144	297	105	243	85	142	72	100	62
30ºC/RH3%	360	360	360	360	360	180	310	122	252	95	176	79	115	67	88	59
30ºC/RH25%	360	360	360	289	360	160	291	113	240	90	153	75	107	65	84	57
30ºC/RH50%	360	360	360	273	360	142	275	105	223	86	135	72	98	62	79	55
30ºC/RH75%	360	360	360	194	323	128	257	99	187	81	121	68	91	59	75	53
36ºC/RH3%	360	360	360	156	268	123	219	90	146	76	105	65	83	57	70	51
36ºC/RH25%	360	281	322	137	246	103	194	84	127	71	95	61	78	55	66	50
36ºC/RH50%	360	211	281	120	226	95	156	78	112	66	88	58	73	52	62	48
42ºC/RH3%	354	161	236	106	191	86	130	73	98	63	81	56	69	54	59	46

Gray: ON-OFF during all the periods until the battery is consumed; NC: no cooling

Table. 3 Predicted core temperature (ºC) with and without FCC at No Cooling (NC) end point for JSLIST/IOTV

	Rest		200W		250W		300W		350W		400W		450W		500W	
	FCC	NC	FCC	NC	FCC	NC	FCC	NC	FCC	NC	FCC	NC	FCC	NC	FCC	NC
24ºC/RH3%	36.9	37.0	37.0	37.1	37.2	37.4	37.3	37.8	37.4	38.6	37.5	39.0	37.6	39.0	37.9	39.0
24ºC/RH25%	36.9	37.0	37.0	37.2	37.1	37.4	37.2	38.0	37.4	39.0	37.5	39.0	37.7	39.0	37.9	39.0
24ºC/RH50%	36.9	37.0	37.0	37.2	37.2	37.6	37.3	38.8	37.4	39.0	37.5	39.0	37.7	39.0	37.9	39.0
24ºC/RH75%	36.9	37.0	37.0	37.2	37.1	38.0	37.3	39.0	37.4	39.0	37.5	39.0	37.8	39.0	38.0	39.0
24ºC/RH100%	36.9	37.0	37.0	37.4	37.1	39.0	37.3	39.0	37.4	39.0	37.6	39.0	37.9	39.0	38.1	39.0
30ºC/RH3%	36.9	37.0	37.0	37.3	37.2	37.7	37.4	38.4	37.4	39.0	37.6	39.0	37.8	39.0	38.0	39.0
30ºC/RH25%	36.9	37.0	37.1	37.4	37.1	37.9	37.3	39.0	37.4	39.0	37.6	39.0	37.9	39.0	38.1	39.0
30ºC/RH50%	36.9	37.0	37.1	37.6	37.2	39.0	37.3	39.0	37.5	39.0	37.7	39.0	38.0	39.0	38.2	39.0
30ºC/RH75%	36.9	37.1	37.1	38.9	37.2	39.0	37.3	39.0	37.6	39.0	37.8	39.0	38.1	38.9	38.2	39.0
36ºC/RH3%	36.9	37.1	37.1	37.6	37.8	38.2	37.5	39.0	37.5	39.0	37.8	39.0	38.0	39.0	38.2	39.0
36ºC/RH25%	36.9	37.2	37.1	38.0	37.2	39.0	37.3	39.0	37.6	39.0	37.8	39.0	38.1	39.0	38.2	38.9
36ºC/RH50%	36.9	37.4	37.1	39.0	37.2	39.0	37.5	39.0	37.7	39.0	38.0	39.0	38.2	39.0	38.2	38.9
42ºC/RH3%	37.1	37.3	37.8	37.9	38.2	39.0	37.4	39.0	37.7	39.0	37.9	39.0	38.1	39.0	38.3	39.0

Gray: ON-OFF during all the periods until the battery is consumed; NC: no cooling

Table 4. Predicted core temperature (ºC) with and without FCC at No Cooling (NC) end point for Level A

	Rest		200W		250W		300W		350W		400W		450W		500W	
	FCC	NC	FCC	NC	FCC	NC	FCC	NC	FCC	NC	FCC	NC	FCC	NC	FCC	NC
24ºC/RH3%	36.8	36.8	37.0	37.1	37.1	38.3	37.3	39.0	37.4	39.0	37.5	39.0	37.8	39.0	38.0	39.0
24ºC/RH25%	36.8	36.8	37.0	37.2	37.1	38.7	37.3	39.0	37.4	39.0	37.6	39.0	37.8	39.0	38.1	39.0
24ºC/RH50%	36.8	36.8	37.0	37.4	37.1	39.0	37.3	39.0	37.4	39.0	37.7	39.0	37.9	39.0	38.1	38.9
24ºC/RH75%	36.8	36.8	37.0	37.7	37.1	39.0	37.3	39.0	37.4	39.0	37.7	39.0	38.0	39.0	38.1	39.0
24ºC/RH100%	36.9	36.9	37.0	38.0	37.2	39.0	37.3	39.0	37.4	39.0	37.7	39.0	38.0	39.0	38.2	38.9
30ºC/RH3%	36.9	37.0	37.0	38.9	37.2	39.0	37.3	39.0	37.6	39.0	37.8	39.0	38.1	39.0	38.2	39.0
30ºC/RH25%	36.9	37.1	37.0	39.0	37.2	39.0	37.3	39.0	37.6	38.9	37.9	39.0	38.1	39.0	38.3	39.0
30ºC/RH50%	36.9	37.3	37.0	39.0	37.2	39.0	37.4	39.0	37.7	39.0	37.9	39.0	38.1	38.9	38.3	39.0
30ºC/RH75%	36.9	37.8	37.1	39.0	37.2	39.0	37.5	39.0	37.7	39.0	38.0	39.0	38.2	39.0	38.3	39.0
36ºC/RH3%	36.9	38.8	37.0	39.0	37.2	39.0	37.6	39.0	37.8	39.0	38.1	39.0	38.2	39.0	38.3	39.0
36ºC/RH25%	36.9	39.0	37.1	39.0	37.3	39.0	37.7	39.0	37.9	39.0	38.1	39.0	38.2	39.0	38.3	38.9
36ºC/RH50%	36.9	39.0	37.1	39.0	37.4	39.0	37.8	39.0	38.0	39.0	38.1	39.0	38.3	39.0	38.3	38.9
42ºC/RH3%	36.9	39.0	37.2	39.0	37.6	39.0	37.9	39.0	38.0	39.0	38.1	38.9	38.3	39.0	38.4	39.0

Gray: ON-OFF during all the periods until the battery is consumed; NC: no cooling

Table 5. Predicted System Duration (SD) (min), SD Extension (Ext) (min), and Battery Time Remaining (BTR) (min) with FCC and CC for JSLIST/IOTV

Environment	SD-CC	Rest			200W			250W			300W			350W			400W			450W			500W		
		SD-FCC	SD-Ext	BTR	SD-FCC	SD-Ext	BTR	SD-FCC	SD-Ext	BTR	SD-FCC	SD-Ext	BTR	SD-FCC	SD-Ext	BTR	SD-FCC	SD-Ext	BTR	SD-FCC	SD-Ext	BTR	SD-FCC	SD-Ext	BTR
24°C/RH3%	208	360	152	188	360	152	145	360	152	115	360	152	78	360	152	34	296	88	0	238	30	0	232	24	0
24°C/RH25%	208	360	152	188	360	152	145	360	152	111	360	152	75	360	152	14	261	53	0	238	30	0	231	23	0
24°C/RH50%	208	360	152	177	360	152	141	360	152	111	360	152	58	329	121	0	241	33	0	237	29	0	202	n/a	29
24°C/RH75%	208	360	152	177	360	152	136	360	152	98	360	152	29	282	74	0	238	30	0	231	23	0	145	n/a	85
24°C/RH100%	208	360	152	174	360	152	130	360	152	76	351	143	0	244	36	0	237	29	0	183	n/a	48	115	n/a	114
30°C/RH3%	193	360	167	120	360	167	82	360	167	45	350	157	0	259	66	0	222	29	0	214	21	0	214	21	0
30°C/RH25%	193	360	167	119	360	167	80	360	167	36	321	128	0	230	37	0	221	28	0	214	21	0	141	n/a	73
30°C/RH50%	193	360	167	115	360	167	73	360	167	14	262	69	0	223	30	0	215	22	0	158	n/a	56	105	n/a	707
30°C/RH75%	193	360	167	114	360	167	51	310	117	0	228	35	0	220	27	0	177	n/a	38	114	n/a	98	86	n/a	124
36°C/RH3%	178	360	182	59	360	182	7	288	110	0	212	34	0	205	27	0	203	25	0	196	18	0	124	n/a	73
36°C/RH25%	178	360	182	58	359	181	0	266	88	0	206	28	0	202	24	0	197	19	0	130	n/a	67	95	n/a	101
36°C/RH50%	178	360	182	54	304	126	0	212	34	0	204	26	0	196	18	0	128	n/a	68	94	n/a	101	77	n/a	118
42°C/RH3%	163	338	175	0	243	80	0	192	29	0	187	24	0	184	21	0	178	15	0	136	n/a	44	96	n/a	83

Key to Column Headings:
SD-CC = System Duration in CC mode, no battery time remaining
SD-FCC = System Duration in FCC mode, battery time may remain
SD-Ext = System Duration Extension = (SD-FCC) – (SD-CC); Extension of System Duration in FCC mode compared to CC mode
BTR = Battery Time Remaining = Minutes of battery life remaining

Key to color coding:

Green	SD-FCC mode exceeds SD-CC mode; battery life remains
Blue	SD-FCC mode exceeds SD-CC mode, but the battery has expired
Yellow	SD-FCC mode is the same or less than SD-CC mode and battery life remains

Table 6. Predicted System Duration (SD) (min), SD Extension (Ext) (min), and Battery Time Remaining (BTR) (min) with FCC and CC for Level A

Environment	SD-CC	Rest			200W			250W			300W			350W			400W			450W			500W		
		SD-FCC	SD-Ext	BTR	SD-FCC	SD-Ext	BTR	SD-FCC	SD-Ext	BTR	SD-FCC	SD-Ext	BTR	SD-FCC	SD-Ext	BTR	SD-FCC	SD-Ext	BTR	SD-FCC	SD-Ext	BTR	SD-FCC	SD-Ext	BTR
24°C/RH3%	208	360	152	206	360	152	186	360	152	130	360	152	55	305	97	0	244	36	0	234	26	0	134	n/a	99
24°C/RH25%	208	360	152	206	360	152	180	360	152	119	360	152	39	278	70	0	242	34	0	206	n/a	29	125	n/a	108
24°C/RH50%	208	360	152	206	360	152	170	360	152	103	360	152	18	256	48	0	240	32	0	178	n/a	56	114	n/a	118
24°C/RH75%	208	360	152	206	360	152	159	360	152	85	346	138	0	250	42	0	238	30	0	158	n/a	75	106	n/a	125
24°C/RH100%	208	360	152	206	360	152	141	360	152	67	319	111	0	244	36	0	235	27	0	142	n/a	90	100	n/a	131
30°C/RH3%	193	360	167	136	360	167	82	355	162	0	234	41	0	224	31	0	175	n/a	42	114	n/a	100	88	n/a	125
30°C/RH25%	193	360	167	135	360	167	64	313	120	0	228	35	0	222	29	0	152	n/a	64	107	n/a	107	83	n/a	130
30°C/RH50%	193	360	167	132	360	167	40	277	84	0	227	34	0	217	24	0	135	n/a	80	97	n/a	116	79	n/a	133
30°C/RH75%	193	360	167	120	360	167	10	238	45	0	223	30	0	187	n/a	29	121	n/a	93	90	n/a	122	74	n/a	137
36°C/RH3%	178	360	182	41	268	90	0	210	32	0	204	26	0	145	n/a	53	105	n/a	91	82	n/a	114	69	n/a	125
36°C/RH25%	178	360	182	33	235	57	0	205	27	0	193	15	10	127	n/a	70	94	n/a	101	78	n/a	117	66	n/a	128
36°C/RH50%	178	360	182	3	210	32	0	202	24	0	156	n/a	45	111	n/a	85	87	n/a	108	73	n/a	121	62	n/a	131
42°C/RH3%	163	241	78	0	188	25	0	183	20	0	129	n/a	53	97	n/a	84	81	n/a	95	69	n/a	107	58	n/a	119

Key to Column Headings:
SD-CC = System Duration in CC mode, no battery time remaining
SD-FCC = System Duration in FCC mode, battery time may remain
SD-Ext = System Duration Extension = (SD-FCC) – (SD-CC); Extension of System Duration in FCC mode compared to CC mode
BTR = Battery Time Remaining = Minutes of battery life remaining

Key to color coding:

Green	SD-FCC mode exceeds SD-CC mode; battery life remains
Blue	SD-FCC mode exceeds SD-CC mode, but the battery has expired
Yellow	SD-FCC mode is the same or less than SD-CC mode and battery life remains

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